Modeling and Experimental Study for Winter Performance of an Earth to Air Heat Exchanger: An Alternative Energy Source for Greenhouse

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ABSTRACT

A complete numerical model has been developed to investigate the potential of using the stored thermal energy of ground for space heating with the help of an earth to air heat exchanger (EAHE) system integrated with the greenhouse located in the premises of IIT, Delhi, India. The analysis was based on quasi-steady state condition. Experiments were conducted extensively during winter period from November 2002 to March 2003, but the model, developed, was validated against the clear and sunny days. The performance of the system was evaluated in terms of total heating potential obtained from EAHE, coefficient of performance (COP) and thermal load leveling. The heating potential of the system has also been standardized by the characteristic curve for greenhouse similar to that of flat plate collector. Temperatures of greenhouse air were found to be on an average 7-8 ^{0}C more than the same greenhouse when operating without earth air heat exchanger. The temperature fluctuations of greenhouse air were also less when operated with EAHE as compared to without EAHE. Predicted and measured values of greenhouse air temperature in the model developed, exhibited fair agreement.

Keywords: Greenhouse, solar energy, earth air heat exchanger, coefficient of performance (COP), thermal load leveling, modeling, India.

1. INTRODUCTION

Heating of greenhouse is one of the most energy consuming activities during winter periods. Lack of heating has adverse effects on the yield, cultivation time, quality and quantity of the products in the greenhouse (Santamouris et al. 1994a). But studies on greenhouse heating strategies have shown that the cost of heating even exceeds 30% of the overall operational cost of the greenhouse (Coffin, 1985). Due to high relative cost of energy, only a small number of greenhouse owners can afford to the use of auxiliary heating systems. The use of low-cost and alternative heating system is therefore of primary importance for a greenhouse to provide optimum indoor conditions during winter months.

Efforts to decrease energy consumption have directed the researchers to use alternative energy sources for heating of greenhouse. Several types of passive solar systems and techniques have been proposed and used (Santamouris et al. 1996, Barral et al. 1999, Bargach et al. 2000, Kumari et al. 2007) for the substitution of conventional fuels with solar energy as a low cost technology. As solar energy is the ideal source of energy for space heating particularly in the northern hemisphere where it is available sufficiently. Also it is practically inexhaustible and its use does not result in pollution. Efforts to harness solar energy have been accelerated during the last decade as world demand for energy grows (Saravia et al. 1997). In all the heat collection systems, the basic strategy is to reduce the heat losses and at the same time to store the surplus energy for use during the energy shortage period. Continuous research in this area and several successful demonstration projects has resulted in rapid advancements and commercialization of these technologies with satisfactory results.

The greenhouses, which utilize solar energy for heat purposes, are equipped with heat collection systems integrated into the cell of the greenhouse. The important heat storage mediums are namely water, latent heat materials, rock bed, buried pipes etc. Out of these storage mediums, buried pipes systems have gained increasing acceptance for better and easy exploitation of thermal energy from the ground (Santamouris et al. 1994b).

In buried pipe systems, the nearly constant and stored thermal energy of earth at a certain depth is usually extracted with the help of an arrangement called earth air heat exchanger (EAHE). The stored thermal energy and thereby the earth's surface and sub surface temperatures at any given location, are determined by the balance between the solar energy absorbed at the surface and heat losses by the outgoing long wave radiations and convective heat exchange with ambient air mass (Sodha et al. 1981). An earth air heat exchanger system herein is defined (Puri, 1987) as the study of heat transfer between soil, tubes and air flowing through the tube when the tubes are placed below the ground surface at a certain depth where temperature of soil remains nearly constant throughout the year. As air travels the length of the tube, it gets heated in the winter period and gets cooled during the summer period resulting in the space conditioning due to its entry into the enclosed space. Earth air heat exchanger system has therefore the potential of being used throughout the year. Hence considering the importance of EAHE as a simple, inexpensive and alternative source of energy, the system has been incorporated in IIT, model greenhouse, New Delhi, during the whole winter period with a view to study its thermal performance for heating of the greenhouse through a model, developed, in the composite climate of India.

2. EXPERIMENTAL PROCEDURES

The EAHE under study was used in the greenhouse located in the premises of IIT, Delhi, India. The climate of the place is composite i.e., it remains hot dry for five months, warm and humid for three months, moderate for one month and cold for three months. The absolute minimum temperature of ambient air during winter period is close to 4 ^{0}C while mean minimum is close to 9 ^{0}C. The greenhouse combined with EAHE was of even span type of greenhouse with floor area 6m x 4m. and was oriented from east to west direction. The EAHE was installed outside in west side of the greenhouse. Total length and diameter of buried pipes used were 39m and 0.06m respectively. EAHE also consisted of PVC pipes buried under bare surface at the depth of 1m in a serpentine manner with 8 nos. of turns. The blower was attached in the suction end of the EAHE. The suction and delivery ends of EAHE were placed in the southwest and northwest corners of the greenhouse for allowing uniform mixing of air. The isometric view of experimental greenhouse integrated with EAHE is shown in Fig. 1a. Experiments were

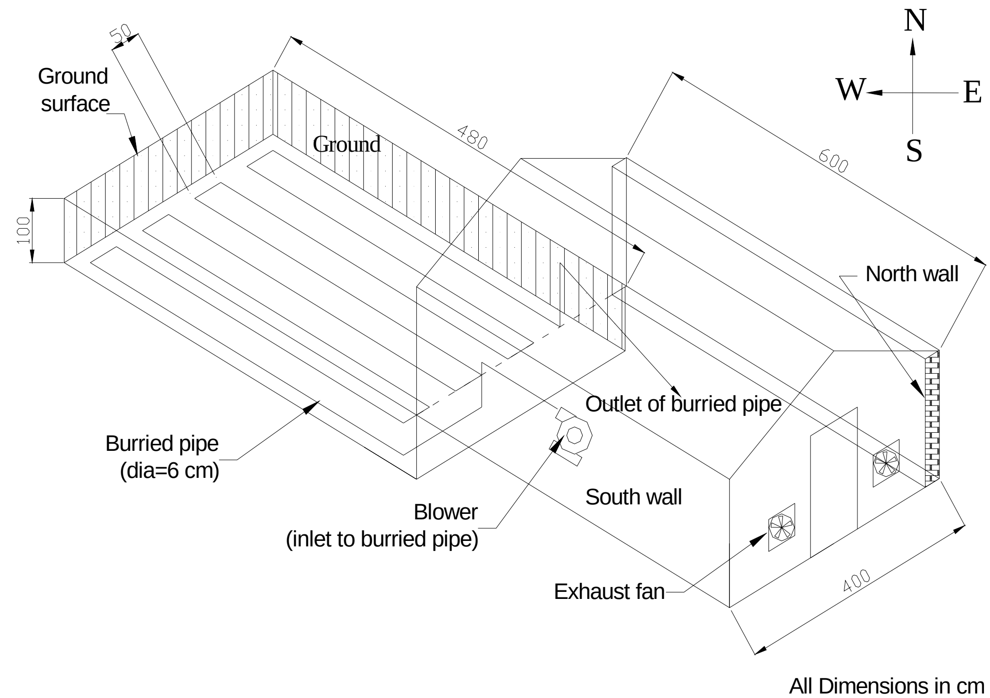

Figure 1a. Isometric view of even span greenhouse integrated with EAHE arrangement

conducted continuously for two days in a week in clear and sunny days from Nov'2002 to March'2003 with 1st day without any heating arrangement and 2nd day with EAHE system. However the experimental validation was done for typical date (clear sunny day) of observations i.e., on 23-01-03 for greenhouse with EAHE, since January is the coldest month for Delhi. Hourly observations of solar radiation and temperatures of air for ambient condition, greenhouse enclosure, suction end and delivery end were recorded during the experimentation with the help of calibrated solarimeter and mercury thermometer, respectively.

3. THERMAL ANALYSIS

The energy balance equations for various components of greenhouse combined with earth to air heat exchanger can be written on the basis of following assumptions:

(i) Analysis is based on quasi steady state conditions,

(ii) There is no radiative heat exchange between the walls and roofs of greenhouse, due to negligible temperature differences,

(iii) Flow of air is uniform along the length of buried pipes,

(iv) Heat flow is one-dimensional.

Energy balance equations for north wall, floor and room air of greenhouse are as follows:

a) North wall

$$\alpha_n(1-r_n)F_n(1-r)\{\sum A_i I_i \tau_i\} = h_{nr}(T|_{y=0} - T_r)A_n + h_{na}(T|_{y=0} - T_a)A_n \quad (1)$$

b) Floor

$$\alpha_g(1-r_g)(1-F_n)(1-r)\{\sum A_i I_i \tau_i\} = h_{gr}(T|_{x=0} - T_r)A_g - h_{g\infty}(T|_{x=0} - T_\infty)A_g \quad (2)$$

At larger depths, the temperature of ground is assumed to be equal to ambient air temperature, $T_\infty = T_a$, then Eq. (2) becomes

$$\alpha_g(1-r_g)(1-F_n)(1-r)\{\sum A_i I_i \tau_i\} = h_{gr}(T|_{x=0} - T_r)A_g + h_{g\infty}(T|_{x=0} - T_a)A_g \quad (3)$$

c) Greenhouse air

$$h_{nr}(T|_{y=0} - T_r)A_n + h_{gr}(T|_{x=0} - T_r)A_g + \dot{Q}_u = \sum A_i U_i (T_r - T_a) + 0.33NV(T_r - T_a) + M_a C_a \frac{dT_r}{dt} \quad (4)$$

The term i.e., $\dot{Q}_u$ in Eq. (4) is the useful thermal energy obtained from EAHE and is expressed by the equation, $\dot{Q}_u = F_R \dot{m}_a C_a (T_0 - T_{fi})$ (5)

where $F_R = 1 - e^{-\frac{2\pi r_1 h_{gf}}{\dot{m}_a C_a} L'}$. Now eliminating $T|_{y=0}$ from Eq. (1) and after rearrangement,

$$h_{nr}(T|_{y=0} - T_r) = F_1 \frac{I_{effN}}{A_n} - U_n(T_r - T_a) \quad (6)$$

where $I_{effN} = \alpha_n(1-r_n)F_n(1-r)(\sum A_i I_i \tau_i)$, $F_1 = \frac{h_{nr}}{h_{nr} + h_{na}}$ and $U_n = \frac{(h_{nr})(h_{na})}{(h_{nr} + h_{na})}$

Similarly eliminating $T|_{x=0}$ from Eq. (3) and after rearrangement,

$$h_{gr}(T|_{x=0} - T_r) = F_2 \frac{I_{effF}}{A_g} - U_g(T_r - T_a) \quad (7)$$

where $I_{effF} = \alpha_g(1-r_g)(1-F_n)(1-r)(\sum A_i I_i \tau_i)$; $F_2 = \frac{h_{gr}}{h_{gr} + h_{g\infty}}$; $U_g = \frac{(h_{gr})(h_{g\infty})}{(h_{gr} + h_{g\infty})}$ and $T_{fi} = T_r$.

Now substituting Eqs. (6) and (7) in Eq. (4) and simplifying, Eq. (4) can be written in the following first order differential equation, $\frac{dT_r}{dt} + aT_r = B(t)$ (8)

where $B(t) = \frac{F(t) + (UA)_{eff} T_a}{M_a C_a}$ and $a = \frac{a_1}{M_a C_a}$; $F(t) = F_1 I_{effN} + F_2 I_{effF} + F_R \dot{m}_a C_a T_o$

$(UA)_{eff} = U_n A_n + U_g A_g + 0.33NV + (\sum A_i U_i)$; $a_1 = U_n A_n + U_g A_g + 0.33NV + (\sum A_i U_i) + F_R \dot{m}_a C_a$

$(\sum A_i I_i \tau_i) = (A_e I_e \tau_e + A_{ww} I_{ww} \tau_{ww} + A_{sr} I_{sr} \tau_{sr} + A_{nr} I_{nr} \tau_{nr} + A_s I_s \tau_s)$

$(\sum A_i U_i) = (A_e U_e + A_{ww} U_{ww} + A_{sr} U_{sr} + A_{nr} U_{nr} + A_s U_s)$; $U_e = U_{ww} = U_{sr} = U_{nr} = U_s = U$

$h_{na} = [\frac{L_n}{K_n} + \frac{1}{h_0}]^{-1}$, $h_{g\infty} = [\frac{L_g}{K_g}]^{-1}$, $U_n = [\frac{1}{h_i} + \frac{L_n}{K_n} + \frac{1}{h_0}]^{-1}$, $U_g = [\frac{1}{h_{gr}} + \frac{1}{h_{g\infty}}]^{-1}$; $U = [\frac{1}{h_i} + \frac{1}{h_0}]^{-1}$, $h_{nr} = h_{gr} = h_{gf} = h_i$. The analytical solution of Eq. (8) can be written as

$$T_r = \frac{\overline{B(t)}}{a}(1 - e^{-at}) + T_{ro}e^{-at} \tag{9}$$

where, T_{ro} is the greenhouse air temperature at $t = 0$ and $\overline{B(t)}$ is the average of $B(t)$ for the time interval 0 and t, and a is constant during the time. From Eq. (9), the temperature of air inside greenhouse, combined with earth air heat exchanger can be determined for analysis.

3.1 Instantaneous Thermal Efficiency (η_i) Characteristic Curves for Greenhouse

The instantaneous thermal efficiency (η_i) is defined as the ratio of thermal energy used in raising temperature of greenhouse air from T_{ro} to T_r to input energy and is expressed as

$$\eta_i = \frac{M_a C_a (T_r - T_{ro})}{t(\sum A_i I_i)} \tag{10}$$

Putting the expressions of T_r, $B(t)$, $F(t)$, $(UA)_{eff}$, a and a_1 in Eq. (10) and simplifying, the instantaneous thermal efficiency becomes, $\eta_i = F'[(\alpha\tau)_{eff} - U_{eff}\frac{T_{ro} - T_{eff}}{I}]$ (11)

Where $F' = \frac{1 - e^{-at}}{at}$; $(\alpha\tau)_{eff} = \frac{F_1 I_{effN} + F_2 I_{effF}}{\sum A_i I_i}$; $U_{eff} = \frac{a_1}{\sum A_i}$; $I = \sum I_i$; at is dimensionless; $T_{eff} = \frac{F_R \dot{m}_a C_a T_o + (UA)_{eff} T_a}{a_1}$ and F' is the efficiency factor for greenhouse (dimensionless). Eq. (11) is the function of design and climatic parameters and is similar to the characteristic equation for flat plate collector (Duffie and Beckman, 1991). This equation is helpful for comparison and standardization of various heating methods inside the greenhouse.

3.2 Computational Procedure and Input Parameters

The energy balance equations derived for greenhouse with EAHE have been solved with the help of a computer program based on Matlab software. The design and operating parameters given in Table-1 have been used as input parameters for the mathematical model developed. The closeness of predicted and experimental values has been presented with coefficient of correlation (c_r) and root mean square of percent deviation (e_r). Solar radiation falling on different walls and roofs of greenhouse was calculated with the help of Liu and Jordan (1962) formula by using the beam and diffuse components of solar radiation incident on the horizontal surface. The heat removal factor for EAHE has been calculated from steady state energy mechanism as shown in Fig. 1b and as per Eq. (5). The mass flow rate of the circulating air was kept constant with 100 kg/hour.

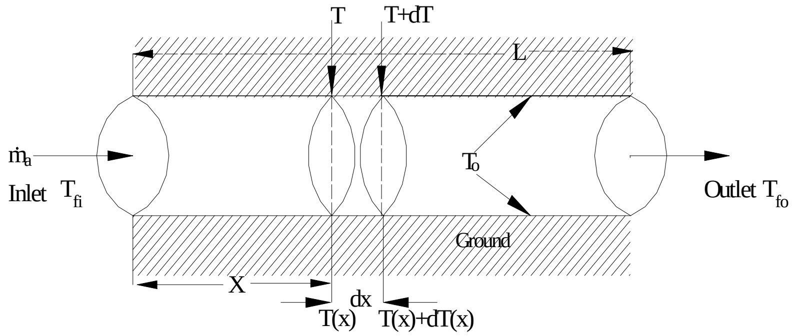

Figure 1b. Energy exchange between ground and flowing air in elementary segment of the buried pipe

The performance of EAHE has been evaluated in terms of thermal load leveling (TLL) (Singh and Tiwari, 2000) heating potential and COP as per the following expressions: $TLL = \frac{T_{r,\max} - T_{r,\min}}{T_{r,\max} + T_{r,\min}}$; $Q_h = \sum \dot{m}_a C_a (T_d - T_{sc}) \Delta t$ and $COP = \frac{output\ energy}{Energy\ spent\ to\ get\ output\ energy}$. Thermal load leveling gives an idea about the fluctuations of air temperature inside the greenhouse. The less the fluctuations, the better is the environment for plants inside the greenhouse. In winter, TLL should have lower values by incorporating heating method due to the increase of $(T_{r,\max} + T_{r,\min})$ as well as decrease of $(T_{r,\max} - T_{r,\min})$ as compared to TLL without heating arrangement. The temperatures of ground i.e., T_o were recorded with the help of data logger through the thermocouples located at the depth of 1.0m under EAHE arrangement.

Table 1. Input parameters used for computations

Parameters	Values	Parameters	Values	Parameters	Values
A_e	8.3 m^2	h_i	2.8 W/m^2 ^{0}C	N	1-300
A_f	24.0 m^2	h_o	5.7 W/m^2 ^{0}C	r_1	0.03m
A_n	12.0 m^2	h_{na}	1.9 W/m^2 ^{0}C	U	1.8 W/m^2 ^{0}C
A_s	12.0 m^2	h_{gr}	5.7 W/m^2 ^{0}C	v	0.5-1.5 m/s
A_{nr}	13.8 m^2	h_{nr}	5.7 W/m^2 ^{0}C	V	60 m^3
A_{sr}	13.8 m^2	K_n	0.84 W/m^{0}C	r_g	0.2
A_{ww}	10.0 m^2	K_g	0.52 W/m^{0}C	r_n	0.2
C_a	1012 J/kg ^{0}C	L'	39m	α_g	0.4
F_n	0.09-0.15	L_g	1m	α_n	0.6
F_R	0.64	$\dot{m}_a$	0.02 kg/s	τ	0.5
h_{gf}	2.8 W/m^2 ^{0}C	M_a	72 kg		

4. RESULTS AND DISCUSSION

The hourly variations of temperature for ambient air, greenhouse air when operating with EAHE for typical winter day (23-01-2003) and without EAHE (22-01-2003) have been presented in Fig. 2. From the figure, it is seen that the minimum as well as maximum temperatures for ambient air, greenhouse air with EAHE and without EAHE varied between 5-20 ^{0}C, 13-24 ^{0}C and 5-28 ^{0}C respectively indicating the less fluctuations of air temperature inside the greenhouse with EAHE as compared to ambient air and greenhouse air without EAHE. This is due to the addition of supplementary thermal energy to the greenhouse by EAHE arrangement. The temperature of ground on the above day at the depth (1m) in which the EAHE system was installed was recorded to be about 23 ^{0}C. The predicted values of greenhouse air have been validated with experimental values for the above typical day (23-01-2003) and they showed fair agreement with (c_r) as 0.98 and (e_r) as 6.93. By examining closely the daily temperature profiles of greenhouse air from Fig. 3, it was found that the delivery temperatures of EAHE were 7-9 ^{0}C higher than the suction temperatures from 7 pm to 9 am (heating of greenhouse air). In between 9 am and 10 am both delivery and suction temperatures became almost same (with zero heating potential obtained from EAHE) and from 10 am to 6 pm, the delivery temperatures were 3-6 ^{0}C less than the suction temperatures (cooling of greenhouse air). As a result of which, the temperatures of greenhouse air were maintained in the range of 13-24 ^{0}C for creating healthy environment for the growth of plants during winter period. Also it was observed that the temperatures of greenhouse air were around 7-8 ^{0}C higher than those of greenhouse air without EAHE system for thermal heating during nighttime.

After knowing the suction and delivery temperatures of EAHE as well as mass flow rate, the diurnal variations of total heating potential obtained from the system for the typical day in the winter months were calculated and have been shown in Fig. 4. From the figure, it is evident that the air in the greenhouse was heated during off-sunshine hours and cooled during sunshine hours (10 am to 6 pm) causing the reduction of its undesirable rise of temperature in the latter period. Similarly the total heating potentials obtained from EAHE for a typical day in each winter months have been computed and presented in Fig. 5. From the results, it is seen that the heating potentials obtained from EAHE were higher in the month of January followed by December, February, November and March. The higher value of heating potential in January (coldest month) is due to the more differences of temperature in suction and delivery ends. The coefficient of performance determined for typical day in each month has also been discussed in Fig. 6 to know the applicability of the system. The values of coefficient of performance were highest in the month of January (2.8), followed by December (2.45), February (2.1) and November (1.94). However, in the month of March its value was below the dashed line (value less than 1) indicating the system needs to be discontinued during this month. The values of thermal load leveling achieved for typical days in each month have been calculated and presented in Fig. 7 in order to know the efficacy of system during the study. From the computed results, it is seen that the values of TLL in each month for greenhouse with EAHE were lower than those without EAHE proving the former to be more effective for reducing the daily swings of temperature of air in greenhouse. After computation of room air temperature, instantaneous thermal efficiency characteristic curve was evaluated from Eq. (11) for the greenhouse with and without EAHE. The equation represents the equation of straight line between efficiency in Y-axis and $(T_{ro} - T_{eff})/I$ in X-axis. The intercept $F'(\alpha\tau)_{eff}$ is the gain term where as slope of gradient $-(F'U_{eff})$ is the loss factor. Instantaneous thermal efficiency curves standardize and compare the heating potential of different heating methods. The slope of gradient (m) in the curve represents the magnitude of various thermal losses from enclosed air to ambient where as the intercept (gain term) refers to the thermal energy rise of the enclosure (greenhouse) air particularly by incoming solar radiation and by other auxiliary heating sources. For heating of an enclosure, the loss factor should be as minimum as possible and the gain term should be as maximum as practicable. From Fig. 8, it is evident that gain term was more in case of greenhouse with EAHE as compared to without EAHE. On the contrary, the loss factor was less in greenhouse without EAHE. The reason for the higher values of loss factor in case of greenhouse with EAHE is due to the more temperature differences between greenhouse air and ambient air resulting in more heat transfer in that condition. However, overall heating effect was more in greenhouse with EAHE as compared to without EAHE due to additional thermal energy gain in the former by the EAHE arrangement. Also theoretical and experimental characteristic curves showed good agreement in both the conditions of experiment.

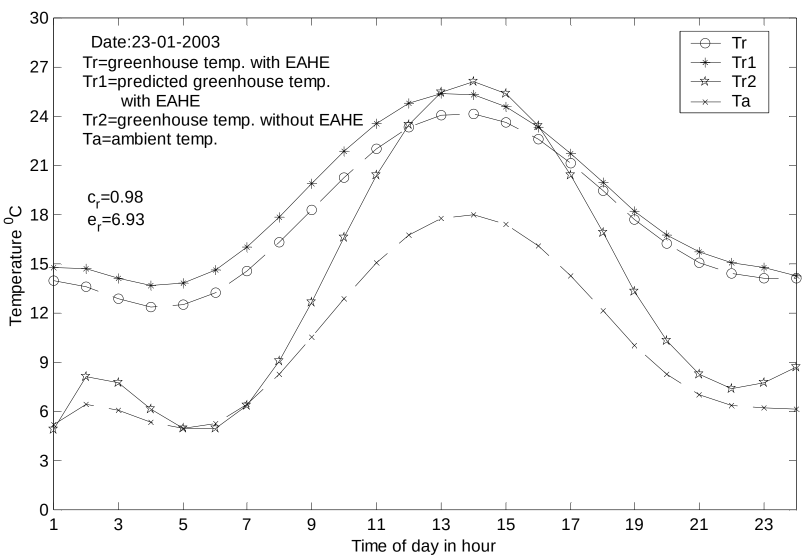

Figure 2. Hourly variations of greenhouse air temperature for typical winter day by EAHE

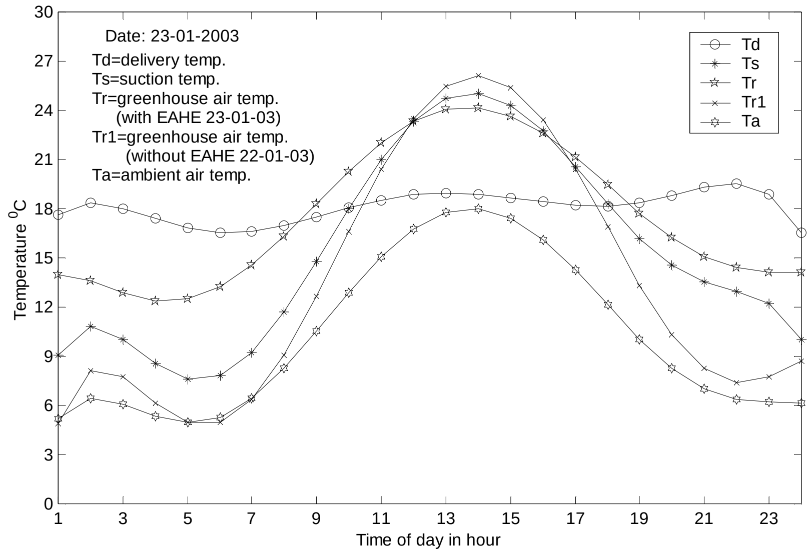

Figure 3. Hourly variations of suction, delivery, greenhouse air (with and without EAHE) and ambient air temperatures during experimentation

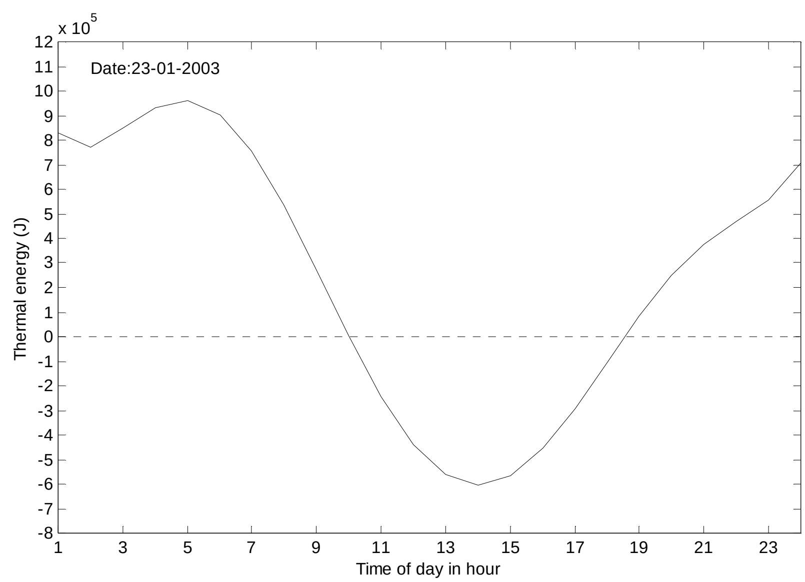

Figure 4. Hourly variations of heating potential by EAHE for a typical winter day

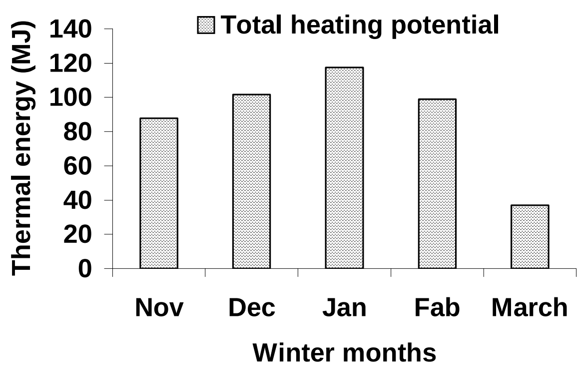

Figure 5. Monthly variations of total heating potential obtained from EAHE during experimentations

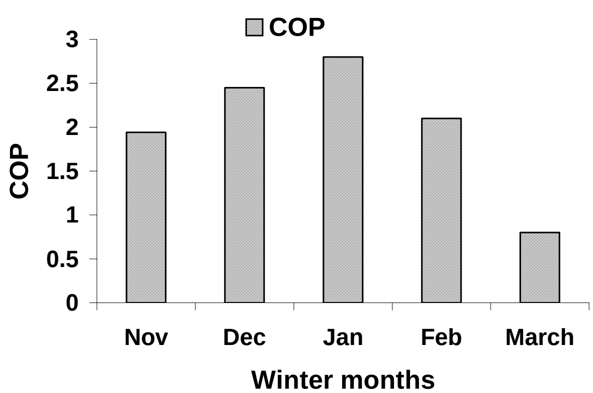

Figure 6. Monthly variations of coefficient of performance (COP) during experimentations

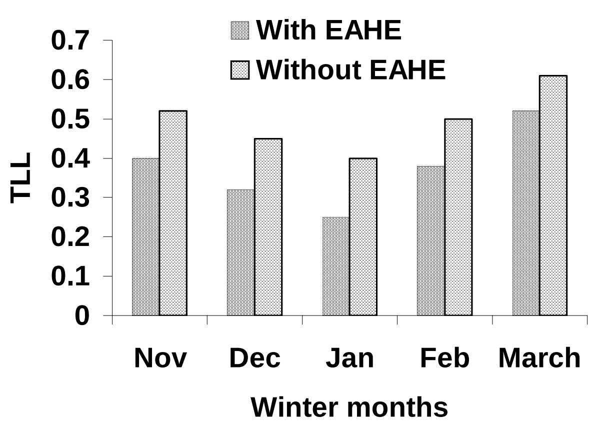

Figure 7. Monthly variations of thermal load leveling (TLL) during experimentations

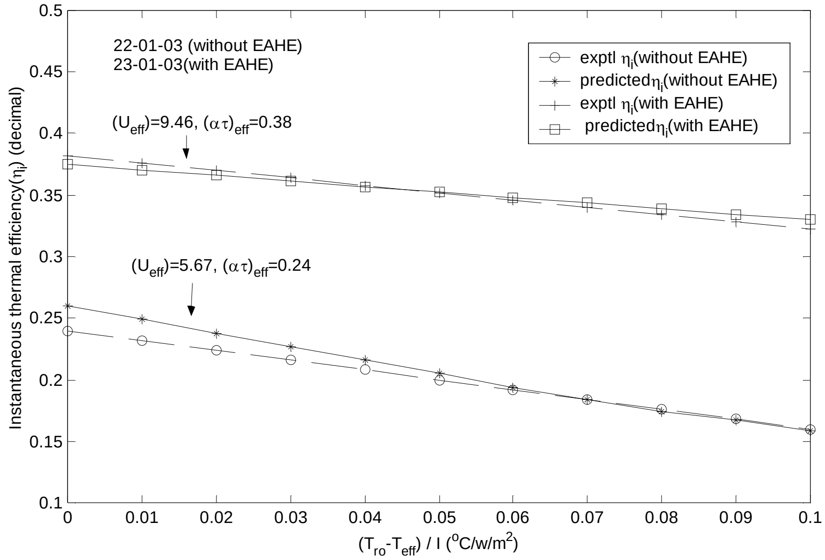

Figure 8. Instantaneous thermal efficiency characteristic curve for greenhouse with and without EAHE

5. CONCLUSIONS

From the above results, the main conclusions for the present study are as follows:

(i) There occurs 7 –8 ^{0}C rise of temperatures for greenhouse air during winter period due to the incorporation of EAHE as compared to without EAHE,

(ii) Relative fluctuations of temperature for greenhouse air are less in EAHE arrangement than without that system

(iii) The predicted and experimental temperatures of greenhouse air in the model developed, with EAHE arrangement exhibit fair agreement.

(iv) The computed and experimental thermal efficiency characteristic curves for greenhouse compare well with each other.

6. ACKNOWLEDGEMENTS

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8. NOMENCLATURE

A - Area, m^2

C_a - Specific heat of air, J/kg ^{0}C

F_n - Fraction of solar radiation falling on north wall, dimensionless, decimal

F_R - Heat removal factor for EAHE from underground earth's surface

h_i - Heat transfer coefficient from greenhouse cover to inside greenhouse air, W/m^2 0C, ($2.8+3.0v$), (Duffie and Beckman, 1991)

h_o - Heat transfer coefficient from greenhouse cover to ambient, W/m^2 0C, ($5.7+3.8v$),(Duffie and Beckman, 1991)

h_{gf} - Convective heat transfer coefficient from underground earth's surface to flowing air inside the buried pipes, W/m^2 ^{0}C

$h_{g\infty}$ - Heat transfer coefficient from floor to larger depth of ground, W/m^2 ^{0}C
h_{na} - Heat transfer coefficient from north brick wall to ambient, W/m^2 ^{0}C
h_{nr} - Heat transfer coefficient from north wall to greenhouse air, W/m^2 ^{0}C
h_{gr} - Heat transfer coefficient from floor to greenhouse air, W/m^2 ^{0}C
I - Solar radiation falling on inclined surface or greenhouse cover, W/m^2
K - Thermal conductivity, W/m ^{0}C
K_g - Thermal conductivity of ground, W/m ^{0}C
L - Thickness, m
L' - Total length of buried pipes (EAHE), m
$\dot{m}_a$ - Mass flow rate of air entering into the buried pipes, kg/s
M_a - Total mass of air in greenhouse enclosure, kg
N - Number of air changes per hour
Q_h - Heating potential offered by EAHE for greenhouse air, J
$\dot{Q}_u$ - Useful thermal energy obtained from EAHE for greenhouse air, W
r - Reflectivity from greenhouse cover, dimensionless, decimal
r_g - Reflectivity from greenhouse floor, dimensionless, decimal
r_n - Reflectivity from north wall, dimensionless, decimal
r_1 - Radius of buried pipe in EAHE, m
t - Time in second
Δt - Time interval in hour
T - Temperature, ^{0}C
T_d - Delivery temperature, ^{0}C
T_o - Temperature of ground in which pipes are spread in EAHE, ^{0}C
T_{fi} - Temperature of inlet fluid or temperature at suction point, ^{0}C for EAHE
T_{sc} - Suction temperature, ^{0}C
U - Overall heat transfer coefficient for greenhouse cover, W/m^2 ^{0}C
U_g - Overall heat transfer coefficient from greenhouse air to floor, W/m^2 ^{0}C
(UA) - Overall heat loss from greenhouse, W/ ^{0}C
v - Velocity of air, m/s
V - Volume of greenhouse, m^3

Greek letters

α - Absorptivity, dimensionless
τ - Transmissivity, dimensionless
∞ - Infinity (at larger depth)
$(\alpha\tau)_{eff}$ -Effective transmittance-absorptance product for greenhouse

Subscript

a - Ambient

e	- East wall of greenhouse
g	- Floor of greenhouse
i	- Different walls and roofs of greenhouse
n	- North wall
r	- Greenhouse room
s	- South wall
nr	- North roof
sr	- South roof
ww	- West wall
eff	- Effective